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Progress in Metal-Detection Techniques for Detecting and Identifying Landmines and Unexploded Ordnance

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INSTITUTE FOR DEFENSE ANALYSES

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PREFACE

This report was prepared for the Joint Unexploded Ordnance Coordination Office in support of a task entitled Technical, Analytical, and Programmatic Support to the Joint Unexploded Ordnance Coordination Office.

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EXECUTIVE SUMMARY

This report assesses the current state of research in the use of metal detectors to detect and identify mines and unexploded ordnance (UXO). This assessment considers both historical efforts in countermine and explosive ordnance disposal as well as emerging results in current programs sponsored within the Department of Defense. This report also uses the priorities and issues developed in three separate workshops sponsored by the Joint UXO Center of Excellence as a basis for measuring progress and establishing potentially attractive avenues for future research and development. Two Joint Unexploded Ordnance Coordination Office (JUXOCO) workshops were conducted in 1997; one focused on magnetometry, and the second focused on active electromagnetic induction (EMI). A follow-up workshop on active EMI was conducted in January 1999. The priorities developed in these workshops included the following items:

- Measurement of target and cultural clutter data in well characterized environments
- Development of wide frequency spectrum EMI
- Development of test sites, protocols, and standard test targets
- Development of time domain and frequency domain EMI models
- Fusion of magnetometer and EMI sensor data
- Fusion with other sensors.

Responding to these priorities, the JUXOCO took three actions:

- Established a pilot test site at Fort A.P. Hill, Virginia, with appropriate protocols and standard mine targets (including clutter)
- Facilitated a collaboration between researchers at Duke University, Auburn University, Ohio State University, and Johns Hopkins University-Applied Physics Laboratory (JHU–APL) to collect and process sensor data from the pilot site
- Sponsored effort through the Army Research Office (ARO) Multi-University Research Initiatives (MURI) program to model buried target signatures in the electromagnetic time and frequency domain.

Significant progress has been made in many different programs to improve EMI time and frequency domain detection of landmines and UXO. In addition to the progress that has been made, it is important to note the objectives and directions of several current DoD programs. The Strategic Environmental Research and Development Program (SERDP) has funded programs for the full-spectrum characterization of UXO, fusion of magnetometry with EMI, and multisensor fusion for UXO detection and identification. The Night Vision and Electronics Directorate (NVESD), U.S. Army Communications and Electronics Command (CECOM), is developing and testing a time domain EMI device to be tested as a vehicle-mounted detector. The MURI program is being continued into a second phase of their earlier efforts.

Given all the past and present efforts, there remains the problem of finding small targets (i.e., less than 5-cm diameter and less than 5 g of metal) that are roughly the same size as the greatest number of clutter objects. The major issue is whether the advances made in using EMI techniques to find and identify larger targets (for example, antitank mines) can be extrapolated to find physically smaller targets that contain less than 5 g of metal, such as antipersonnel mines and small UXO. The frequency domain appears to offer advantages when looking for very small or low-metal targets, but the time domain does well for larger metal targets. A combined time and frequency domain detector may prove to be the optimum system. Future resources should be applied to accomplish the following research goals and objectives:

- Model, construct, and test a frequency-domain detector optimized to find small UXO and mine targets roughly the size of the U.S. M–14 landmine.
- Model, construct, and test a time-domain detector optimized to find small targets and voids as above.
- Model a combined time/frequency domain detector. If modeling results offer potential improvements over separate time- and frequency-domain detectors, construct and test a combined time/frequency-domain detector optimized to find small UXO and mine targets.
- Model and measure the effects of placing targets and clutter in the sensor "sweet spot" or very near the point of greatest receiver sensitivity. Clutter in close proximity to targets will alter target signatures; this effect needs to be assessed.
- Model and measure the optimized detectors in loam, sand, and magnetite soils with a range of representative soil moistures.
- Develop a set of small clutter objects to be modeled and measured.

- Preserve theoretical model calculations and data measurements so that future designs can use the model to predict and evaluate sensor performance.
- Conduct field tests at the pilot test site and compare performance of optimized detectors to baseline performance of the AN PSS–12 and Geophex GEM–3 detectors.
- Apply advanced signal-processing techniques to demonstrate the full ability of optimized EMI performance against small UXO mine and clutter targets.

I. BACKGROUND

A. CURRENT DETECTION TECHNIQUES

Mines and unexploded ordnance (UXO) can be detected using active electromagnetic induction (EMI) techniques and passive magnetometer techniques. Active EMI techniques rely on the detection of eddy currents induced in metallic objects. The eddy currents are excited by an ac current generated in a transmit coil located in the head of the detector. Eddy currents induced in the target produce a secondary magnetic flux. A second circuit utilizing a search coil detects the flux caused by the eddy currents. Because both the excitation and the induced field fall off as D^{-3} (where D is the distance from the detector to the target), the total detection capability falls off as D^{-6}. Inasmuch as the induced field may be made greater than the remanent field near the soil, the sensitivity of the active EMI sensor is usually greater than that of a passive system. Most military mine detectors are EMI devices that recognize a preset threshold in the flux induced in the search coil. Because many of these detectors perform no discrimination between signals that meet threshold requirements, handheld EMI detectors suffer from large numbers of false alarms caused by their response to metal clutter.

Passive systems use Earth's magnetic field as the signal source. Magnetic materials such as buried ferrous ordnance distort Earth's magnetic field; this distortion is detected by a magnetometer. There are two different types of magnetometers. The total field magnetometer measures the magnetic field without respect to the orientation of the magnetic field. The vector magnetometer measures the projection of the magnetic field along a particular direction. (A gradiometer measures the spatial rate of change of the magnetic field.) For magnetometers, the magnetic field falls off as D^{-3}. For a gradiometer, the field falls off as D^{-4}, but the faster fall-off of the field gradient is compensated for by increased signal resolution. Theoretically, magnetometers should be able to detect all ferrous mines and UXO targets at burial depths of 0–15 cm. Actual detections are limited by clutter responses from shrapnel, variations in soil properties, platform noise, and man-made debris. Handheld magnetometers are a relatively mature technology in which quite capable instruments are emerging at lower and lower prices. Although used widely for

UXO detection, magnetometers and gradiometers are not generally used for mine detection.

B. JOINT UNEXPLODED ORDNANCE COORDINATION OFFICE (JUXOCO) WORKSHOPS AND INVESTMENTS

From 18 to 19 November 1997, a magnetometry workshop was conducted by the Joint Unexploded Ordnance Coordination Office (JUXOCO). Twenty-two technical representatives from universities, industry, the Department of Defense (DoD), and the Department of Energy (DOE) discussed magnetometry, its limitations, and future technology investments. The following were the major suggestions for improvements in magnetometry:

- Management of target and clutter signal data in known environments
- Sensor fusion
- Fuse magnetometry and active EMI.

In the time elapsed since this initial workshop, ongoing test and evaluation of magnetometry fused with EMI at Jefferson Proving Ground (JPG) IV has demonstrated improved clutter rejection. The Naval Research Laboratory (NRL) has made progress by simultaneously collecting magnetometer and induction data in its Multi-sensor Towed Array Detection System (MTADS). Additional work is required to obtain co-registered data sets for different sensors at different locations.

An initial JUXOCO workshop on active EMI detection technologies was conducted on 9 and 10 December 1997. Technical representatives from a wide variety of universities, industry, and DoD organizations worked together to define EMI technology, EMI metrics, and recommended future EMI technology investments. Twelve potential EMI investments were identified and discussed in this workshop. Three of the potential twelve EMI investment items were given the highest priority:

- Full spectrum EMI (use entire frequency domain)
- EMI system model (predict response of specific targets and clutter)
- Standard test sites/protocols/targets.

In response to the workshop priorities and its clear Office of the Secretary of Defense (OSD) mandate, JUXOCO made seminal investments in the following areas. JUXOCO sponsored the design and construction of a pilot test site to provide a place where "well-truthed" signal data that would be independent of human operators could be gathered. This pilot test site was established in conjunction with the Multi-University

Research Initiatives (MURI)-sponsored data collection to determine baseline performance of handheld metal detector systems.

The test site established at Fort A.P. Hill, Virginia, was initially set up so that metal detectors could acquire benchmarked data against standard mine and clutter targets. UXO and other sensors would be added later. Initial objectives included establishing:

- Baseline performance of the U.S. Army AN PSS–12 mine detector
- Test and evaluation of advanced algorithms
- Evaluation of standard protocols and data formats.

The site layout included two testing grids shown in Figure I–1. The calibration lanes contain specific types of mines, as well as ferrous and nonferrous clutter buried at known depths. The mines range from high metallic to very low metallic content. Eleven different types of mines are employed in the test grids. The antipersonnel mines are the VS–50, TS–50, PMA–3, M–14, T–72, and VAL 69, and the antitank mines are the M–19, TMA–4, VS2.2, TM–46, and TM62P3. All these types are included in the calibration lanes, along with representative clutter objects.

The handheld test site was constructed on a relatively flat and clear area at Site 71 Alpha at Fort A.P. Hill. The top 6 in. of soil was graded and the metal clutter removed. The metal clutter was saved for use in the test grids. The test targets and clutter items were buried in the blind test grid at the precise centers of the individual test squares. Because theoretical calculations show significant changes to time and frequency domain signatures of small mines buried in different soils, precise soil moisture and dielectric properties were measured at each grid square (Figure I–2).

Receiver operating characteristic (ROC) curves were calculated from measured data for the PSS–12 and Geophex GEM–3 detectors at the Fort A.P. Hill pilot test site. A wide range of antipersonnel and antitank mines were used as targets and represented a spectrum of low metallic content mines to high metallic content mines. These measurements also laid the foundation for algorithm improvement analyses and evaluation. Figure I–3 shows an arbitrary ROC curve with both a baseline sensor characterization (lower curve) and improvements obtained from the application of signal processing algorithms (upper curve).

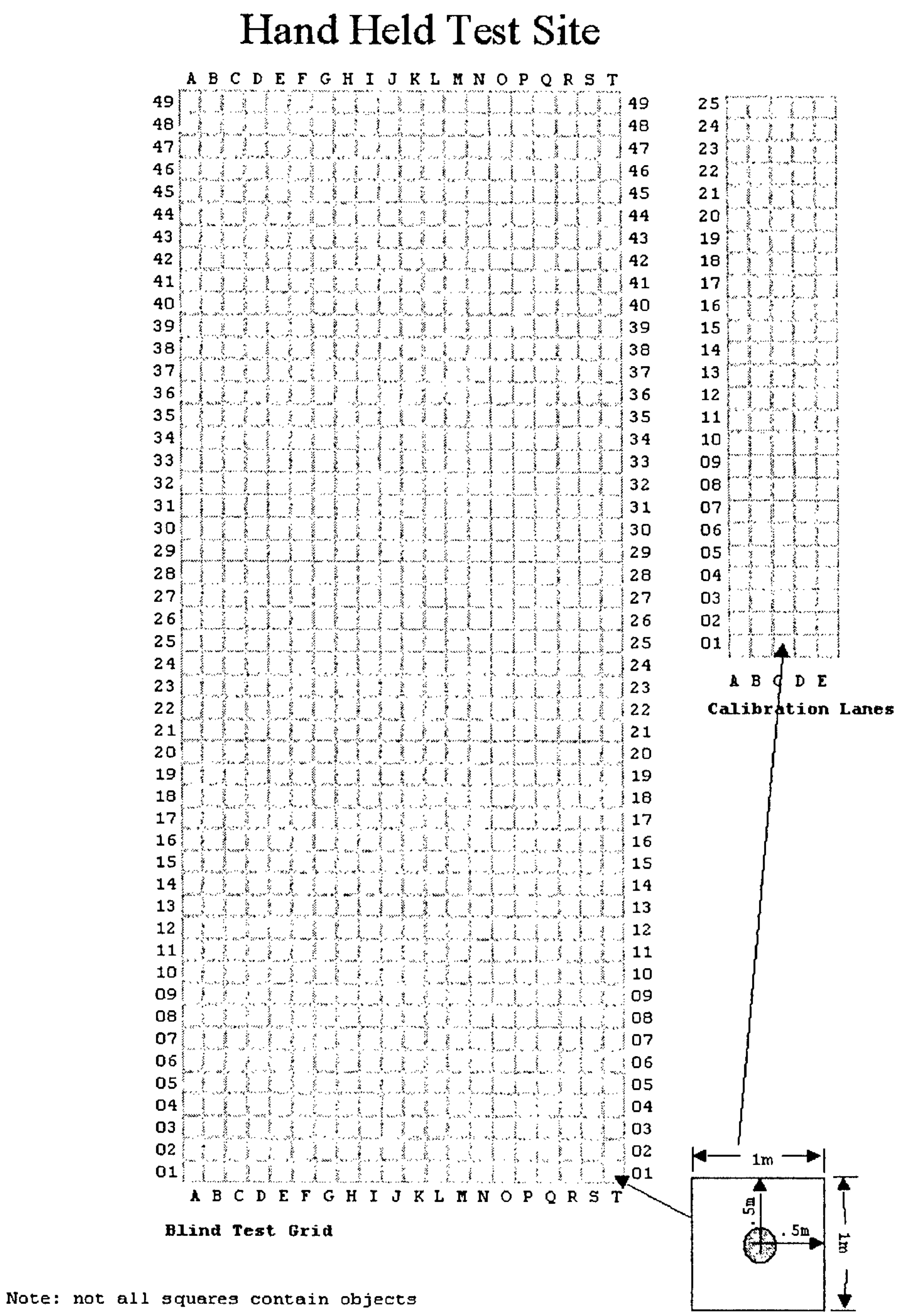


Figure I–1. JUXOCO Pilot Test Site

One of the principal objectives of the JUXOCO pilot test site is to quantitatively identify improvements that are made both in hardware and software. The chance diagonal (0,0:1,1) of Figure I–3 corresponds to a coin toss where the ratio of P_d/P_{fa} equals unity. The extent to which the sensor/algorithm curves move further up to the left of the chance diagonal is the measure of improvement brought about by the sensor/algorithm.

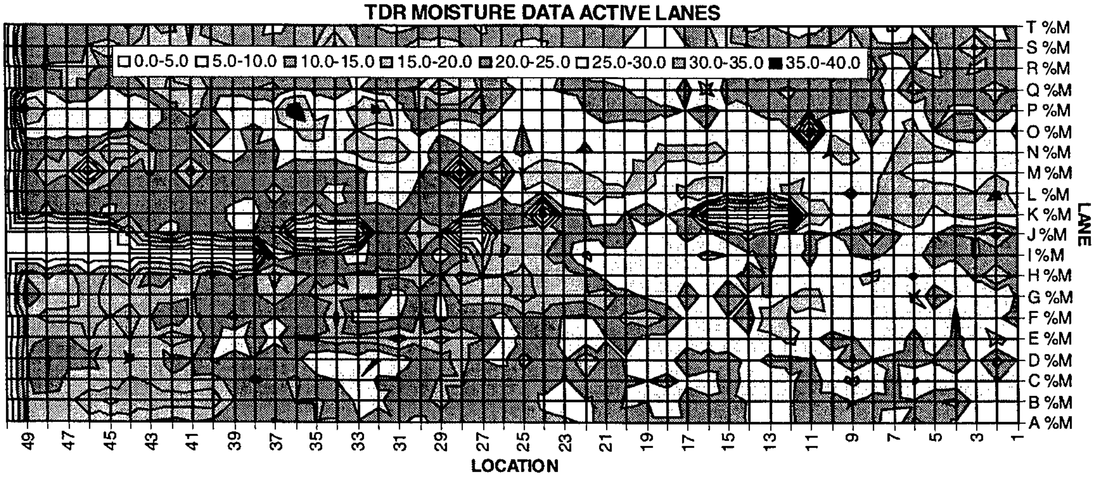


Figure I–2. Moisture Data for Active Lanes

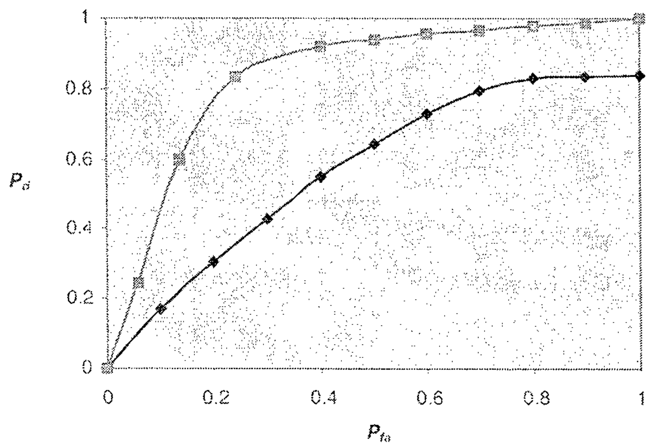


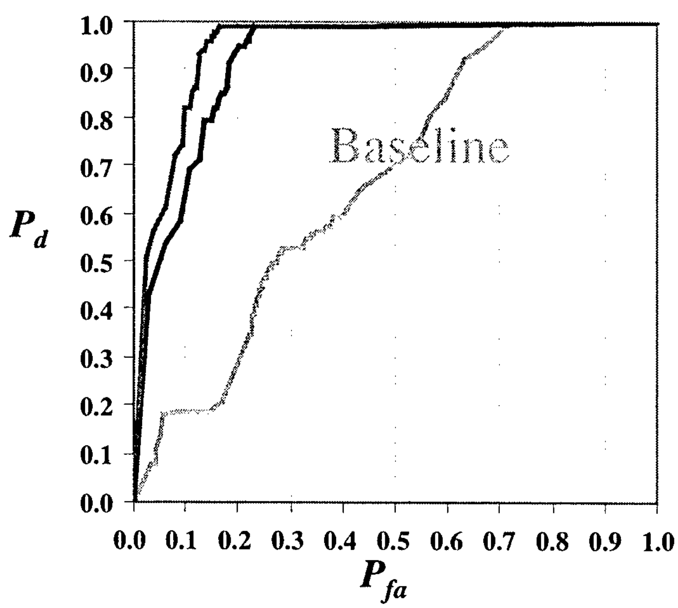
Figure I–3. ROC Curve Showing Detector Baseline and Automatic Target Recognition (ATR) Improvement

Therefore, the ROC curves can characterize individual sensors as well as the improvements in detection performance. ROC curves also reflect the ratio of the signal to noise plus clutter inherent in a specific target and environment, so it is important that claims for improvement be based on identical targets and environments. Most important, the AN PSS–12 and GEM–3 baseline ROC curves serve as the reference point for all signal-processing techniques that may be developed for these two types of detectors. The method used to develop the baseline was to measure the energy in the return signal directly over the center of the target. By "thresholding" this energy, a baseline ROC was calculated. Spatial data was also taken in a cross pattern over the center point every few inches, depending upon the sensor and target.

JUXOCO sponsored signal-processing analyses at Duke and Auburn Universities to evaluate different approaches for evaluating the EMI signatures collected in the testing at the Fort A.P. Hill pilot test site. The generalized likelihood ratio test (GLRT) requires mean signatures and noise covariance but does not allow for the arbitrary scaling that occurs with soil moisture changes and target depths of burial that occur in field measurements using EMI detectors. A modified GLRT (nGLRT) was developed at Duke University. The modifications generally require that the GLRT is applied to meaningful subsets of data such that

1. A center threshold energy is set so that responses less than a predefined threshold are assigned a "no target" status.
2. The range in energies from the detector responses in the calibration lanes is used to determine to which target each response is related (i.e., comparing like items to like items).
3. The nGLRTs are calculated between each observed signal and the subset of N selected signals.
4. Spatial information is incorporated by utilizing features extracted from the nGLRTs across space.

Figure I–4 shows the baseline for the GEM–3 frequency domain detector, together with improvements gained by using an nGLRT for both center point and spatial processing.



GLRT—Center Point

Factor of 3.5 False Alarm Reduction @ P_d = 0.95

GLRT—Spatial

Factor of 5 False Alarm Reduction @ P_d = 0.95

Figure I–4. Baseline Measurements and Algorithm Improvements to the GEM–3

The GEM–3 detector exhibits a large improvement over the chance diagonal. The use of center-point-modified GLRT processing decreases the false alarm rate by a factor of 3.5, while the spatial modified GLRT processing decreases the false alarms by a factor of 5. Figure I–5 shows the additional improvement that can be made over the spatial GEM–3 data by fusing it with the AN PSS–12 detector.

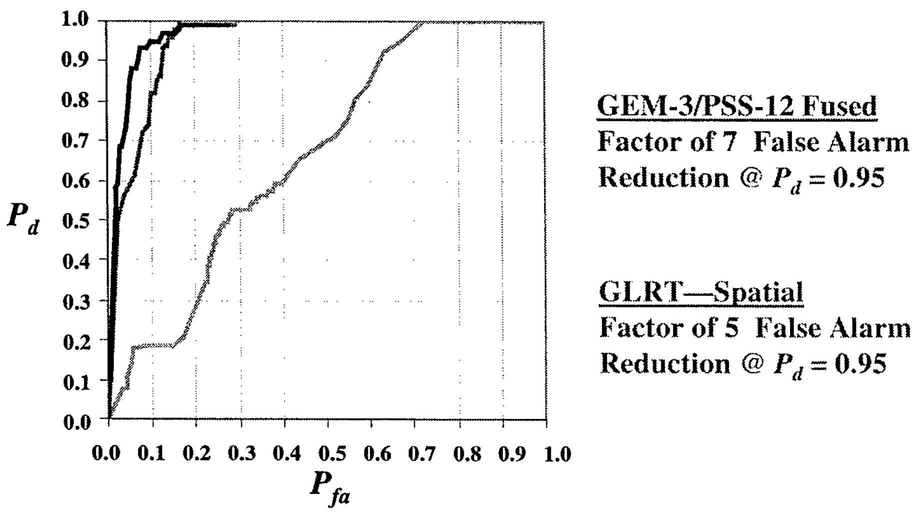


Figure I–5. Fusion of GEM–3 and AN PSS–12 Data Using GLRT Algorithm

The baseline performance of the AN PSS–12 detector was measured by Auburn University. Figure I–6 shows both the baseline performance of the AN PSS–12 and the improvements attainable with a spatial symmetry algorithm.

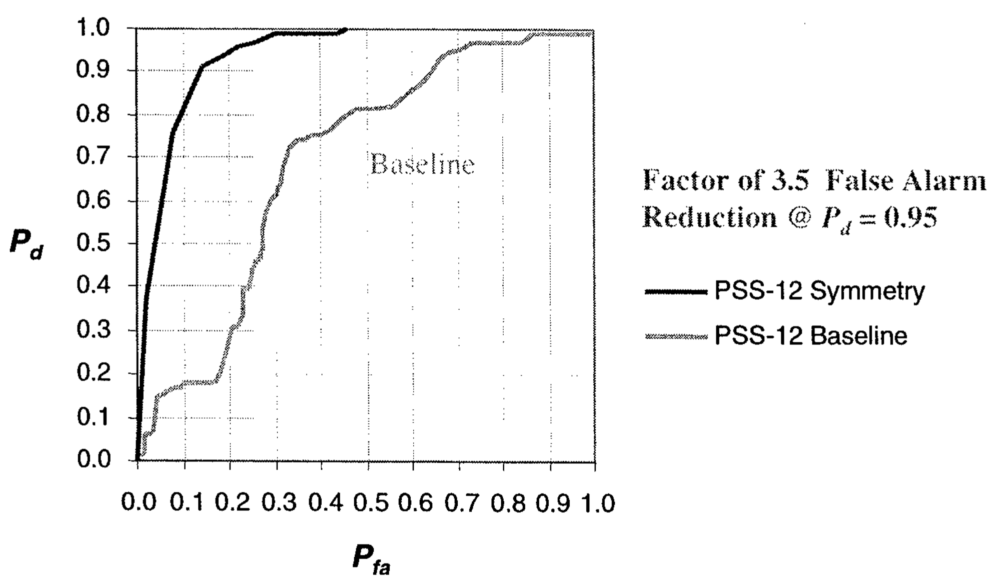


Figure I–6. Baseline Performance of AN PSS–12 and Spatial Algorithm

Other examples of reduction of false alarms are the results achieved by Johns Hopkins University-Applied Physics Laboratory (JHU–APL) using their prototype time domain electromagnetic induction detector (TEMID). Figure I–7 shows both the baseline performance of the TEMID and the improvements that can be obtained from the JHU–APL decay curve signature algorithm. The TEMID data is preliminary and does not use spatial information but only decay rate data at the center point. Further improvements in the TEMID performance are expected as more data is gathered and more sophisticated signal-processing techniques applied.

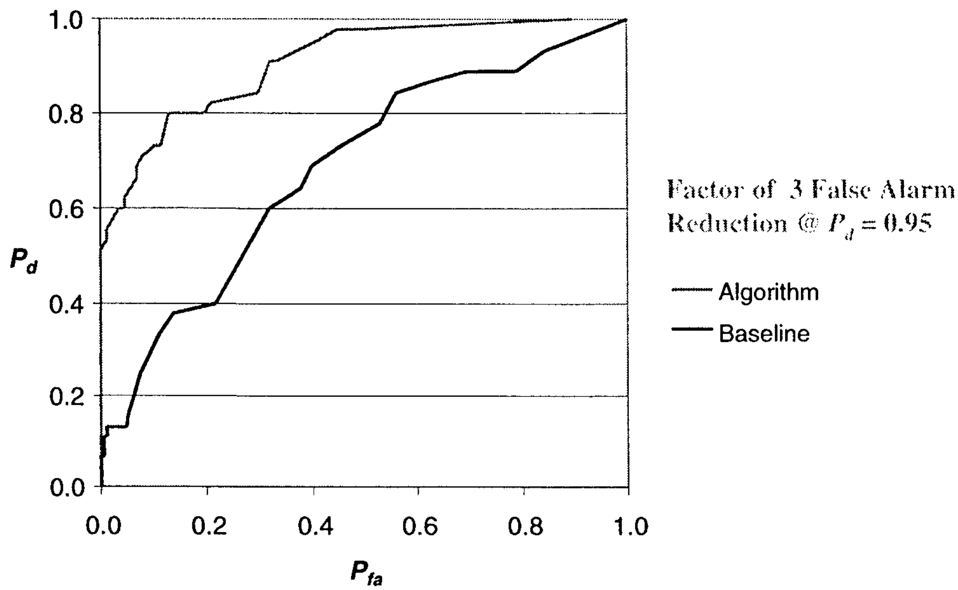


Figure I–7. TEMID and Decay Algorithm

Measurements with the GEM–3 sensor showed that signatures for buried low-metal mines differed dramatically from signatures made in "free" air. This result led JUXOCO to ask Duke University to model this phenomenon. Theoretical calculations at Duke University were made to compare predictions of mine frequency spectra and time constants to those actually measured against specific targets in air and buried in soil. Method-of-moments (MoM) and extended-Born analysis were developed for the electromagnetic response of a buried low-loss target such as a plastic-cased or low metallic mine embedded in soil. Modeling results indicated that at higher frequencies the effects of the plastic target serves as an insulator, and this effect dominates the signature rather than the small metal components. This effect was called a "void" effect. The void signature was studied as a function of soil water content. A strong enhancement of the EMI signature to accompany increases in the soil water content was computed. Experimental evidence for void detection and the effects of conductive soils were subsequently demonstrated by

JHU–APL experiments conducted at JUXOCO pilot test site and also at Auburn University.

From 21–22 January 1999, in a follow-up active EMI Workshop given by the JUXOCO, research conducted since the first workshop was presented and discussed. The following were general conclusions of this meeting:

- Current EMI sensor and algorithm performance is highly site dependent
- More target and clutter data need to be generated
- Although progress is being made in fusing magnetometry and EMI sensors, additional co-registered, multisensor data need to be collected
- Modeling is key to understanding and bounding the problem
- Additional algorithm evaluation needed for all sensor data.

This report addresses needed new investments in the area of metal detection to define or act as a catalyst to define promising research avenues. Not surprisingly, there exist a large number of ongoing efforts in metal detectors, so it is worthwhile to quickly scan these investments and their emerging results.

C. PROGRESS IN METAL DETECTION

Although not an exhaustive summary of current work in improving the performance of metal detection technology, the following discussion illustrates the breadth and types of research currently being performed.

1. Theoretical Work

The electromagnetic properties of a material can be characterized by its permittivity, ε, magnetic permeability, μ, and electrical conductivity, σ. The use of electromagnetic energy to detect mines and UXO requires detecting the differences—in one or more of the three quantities above—between the object and the surrounding medium. For linear, homogeneous, and isotropic media, these properties are expressed in the frequency domain as

$$\vec{B} = \mu\vec{H}$$

$$\vec{J} = \sigma\vec{E}$$

$$\vec{D} = \varepsilon\vec{E} \quad ,$$

where $\vec{B}$ is the magnetic flux density, $\vec{H}$ the magnetic field intensity, $\vec{J}$ the current density, $\vec{E}$ the electric field intensity, and $\vec{D}$ the electric flux density. For anisotropic media, ε, μ, and σ are 3×3 tensor matrices instead of constants or scalar functions of frequency. Maxwell's equations give all of the quantities that describe the propagation of electromagnetic waves in terms of the propagation constant, k, where

$$k^2 = \omega\mu(\omega\varepsilon - \sigma) \quad .$$

The electrical properties can be written as complex quantities

$$\varepsilon = \varepsilon' - \varepsilon''$$

$$\sigma = \sigma' - \sigma''$$

$$\mu = \mu' - \mu'' \quad .$$

The imaginary part of the propagation constant contains the information about energy loss in a medium during propagation. Solving

$$\nabla^2 E + k^2 = 0$$

for targets of volume, V, in the limits for both poor ($\sigma = 0$) and excellent ($\sigma = \infty$) conductors yields the following results. For the poor conductor, the frequencies at which singularities in the frequency occur are found to be inversely proportional to the volume, V, the permeability, μ, and the permittivity, ε. For the perfect conductor the frequency residue is inversely proportional to the volume, V, the permeability, μ, and the conductivity, σ. The frequency domain yields important detection information for both the presence of conducting targets and voids. The method of moments has been used to calculate residues for a variety of objects, both metallic and low-loss dielectrics. This approach can model both metallic and nonmetallic mines and UXO. This approach also offers potential natural discrimination of targets from clutter based on the physical properties of the targets and soil (V, ε, μ). This approach is also well suited to complement experimental methods that operate in the time domain.

A model has been developed in which the time decay curves are processed by means of a singularity expansion method (SEM) to characterize the time constants and amplitude of the set of decay curves that constitute the magnetic polarizability. The poles of the magnetic polarizability describe the responses of the target. By limiting the number of exponential terms to three,

$$D(t) = A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + A_3 e^{-t/\tau_3} \quad ,$$

it has been demonstrated in Advanced Technology Demonstrations (ATD) conducted by the U.S. Army that the poles and residues in the form of decay time constants, τ_i, and the amplitudes, A_i, can be used to identify specific targets. By plotting the resulting amplitudes (residues) versus the time constants for each of the three terms, experimental data exhibit separation of mines from other objects present during ATD data collection.

The difficulty with the pole and residue approach is that there is no physical reason to limit the solution to three or any other number of exponential terms. Clearly, as the number of exponential terms increases, the goodness of fit improves while at the same time placing greater ambiguity in the values of the poles and residues. In addition, recent work sponsored by Strategic Environmental Research and Development Program (SERDP) indicates that the large increase in the variance that occurs when estimating more than one pole can cause considerable confusion in estimating the true poles of an object. Because variations in parameters such as target orientation and soil conductivity occur even within the same test environment, it is not clear that the pole/ residue approach will be robust in largely different environments and with new test targets if high probabilities of detection and low probabilities of false alarms are to be maintained.

Extensive time and frequency domain signal-processing analyses have been conducted using a "modified" generalized likelihood ratio test. Dramatic improvements in reducing false alarms are evidenced in improved ROC curves, as discussed in the previous section. These techniques have been successfully applied to a variety of EMI, radar, and nuclear quadrupole resonance (NQR) test data. Work with optimized filters has demonstrated improved classification performance. Fuzzy logic neural networks and matched filters have been demonstrated that can identify specific large mines. The improvements demonstrated using signal-processing techniques have been limited to specific, well characterized data generally taken with the targets centered directly under the detector search coil. The general applicability of these techniques to reduce false alarms in actual operational remediation tasks has not been demonstrated.

2. Experimental Work

Frequency-domain measurements at JPG demonstrated real and imaginary responses of some types of UXO and mines in air. These experimental signatures agree in shape with theoretical calculations. The degree to which these signatures are changed by burial in different soil is an important issue. Calculations involving smaller objects clearly show that the type of soil, the target size, and its burial depth drastically alter the observed responses from those measured in air. EMI spectroscopy is limited at this time to measurements of targets in air and is not necessarily appropriate for small targets buried in different soils.

EMI-induced time constants of different targets are an excellent method for probing the target material to determine its material properties, the target size, and the target shape. Time domain measurements in the 0.1- to 10-μsec interval reveal small targets or details of transmitter turn-off in larger targets. During the time interval 1–30 μsec, resistive losses attenuate the current. Currents diffuse through the target during the interval 20–1,000 μsec. In the late time period, that is, times greater than 1 ms, currents decay at a rate determined by their target size, conductivity, and permeability. Significant experimental success has been achieved for large mines and UXO during the past 2 years. As stated earlier, use of fuzzy logic networks in one application and use of the magnetic polarizability in another application led to target identification and separation of mines from the clutter present during experimentation.

Broadband (dc to 10^6 Hz) time domain measurements have been made with antenna time constants less than 2 μsec. These measurements were performed on a variety of mine type and clutter targets. With this type of time domain sensor performance, it may now possible to differentiate and identify small antipersonnel mine targets and measure the time constants associated with different soil types and soil moistures.

As the number of different high-resolution magnetometers continues to increase with corresponding decreases in prices, fuzed magnetometer and EMI methods that wed the best characteristics of both technologies are being demonstrated. The theoretical and experimental successes in the EMI frequency and time domain clearly point to the potential inherent in fusing EMI signature features with magnetometer features. Using neuron type and other types of networks, excellent results have been shown for discriminating between UXO and clutter objects.

NQR also uses an active electromagnetic pulse to stimulate quadrupole resonance on explosives such as RDX and trinitrotoluene (TNT) used in plastic or wood-cased landmines. Recent experiments demonstrated a rapid detection capability of 100-gram samples of RDX with time constants on the order of milliseconds. Detection of TNT is more difficult, with time constants generally on the order of 3–10 seconds. Although there is no NQR response for explosives in metallic cases, the response of the metallic case can be used to identified buried metallic objects.

Figure I–8 shows the strengths and weaknesses of different metal-detection technology approaches. New capabilities to identify different types of large mines and UXO and to distinguish large targets from clutter have been demonstrated both analytically and experimentally. The obvious question is whether these advances can be extrapolated into improvements in the tougher problems of finding smaller targets and voids such as small antipersonnel land mines. Certainly, time domain and frequency domain measurements can be used to improve UXO clutter rejection to depths of 1 to 3 meters. These improved target spectra data should offer significant potential for improved fusion of magnetometer data with EMI data. Advances in magnetometry and in EMI, both time domain and frequency domain, offer fusion and signal processing to improve performance against smaller, more difficult targets.

Technology	Strengths	Weaknesses
Threshold Techniques	Relatively inexpensive, widely available	No discrimination of clutter. No ability to identify targets.
Time Domain	Detection and identification of large metallic targets. Detection of voids in conducting soils.	Unknown ability to detect and discriminate small targets from clutter. Unknown ability to detect small voids.
Frequency Domain	Detection and identification of metallic targets through measurement of frequency spectra. Void detection in conducting soils.	Unknown ability to detect and discriminate small targets from voids. Unknown ability to identify small targets in conductive soils.
Magnetometry	Relatively inexpensive, precision measurements.	Difficulty in discriminating smaller targets such as mines from clutter objects.

Legend: New Capabilities; Areas needing new experiments and analysis

Figure I-8. Status of Metal Detection Technology Approaches

II. DETECTOR-BASED ISSUES

Production detectors are the result of tradeoffs in size, weight, type, and life of battery; reliability; ease of operations; ease of repair; and total cost to compete successfully in the market place. Although these issues are important in the selection of detectors to perform certain tasks or functions, there exists an objective set of electromagnetic issues that also drive production design decisions. Not surprisingly, the design tradeoffs result in detectors that perform well against certain types of targets or in most environments, but do not perform as well against different targets or in particular environments. To understand the potential of new detectors, it is important to review the underlying electromagnetic issues that shape the performance of any detector, particularly with respect to exploiting time and frequency domain measurements.

A. NOISE FACTOR IN MINE DETECTORS

Since noise is always present, any signal amplification results in noise amplification as well. The smallest detectable signal in a detector is limited by noise from internal and external sources. Internal noise is generated within the amplifier and the sensor. The internal noise can be controlled by the manufacturer. More difficult to control is external noise, which includes cosmic and atmospheric noise picked up by the antenna, man-made noise from machinery and radio transmitters, and ground clutter. The system noise factor of a mine detector is simply the ratio of the input signal-to-noise ratio (SNR) to the output SNR. The system noise factor is measurable and generally depends on the operating frequency and the dynamic range of the detector. Figures II-1 and II-2 show the minimum and maximum external noise figure, F_a, for atmospheric noise as a function of frequency. In the frequency range where most threshold of EM detectors operate (1–10 kHz), there is little seasonal, diurnal, and geographic variation.

B. DYNAMIC RANGE OF MINE DETECTORS

The threshold of target detection dictates the maximum sensitivity of any detector. False alarms result when the noise level exceeds a preset threshold level. Because the overall system sensitivity is very important, trade-offs must be made between bandwidth, threshold, noise, and false-alarm rate. Setting high threshold levels necessarily limits the dynamic range. Establishing variable detection thresholds through frequency and time domain measurements increases the usable dynamic range of the detector system.

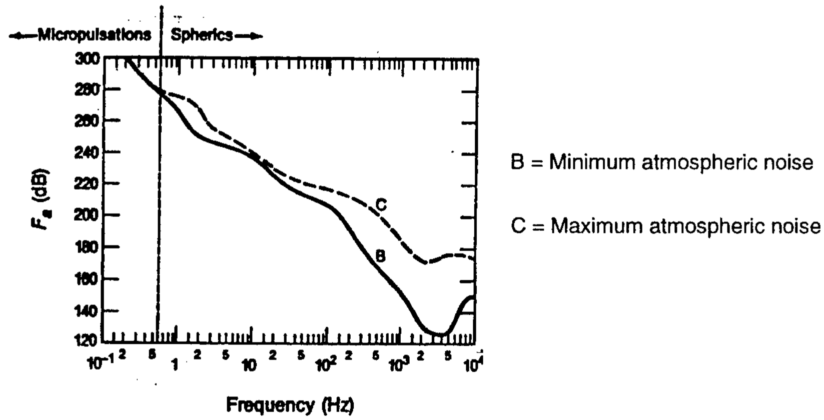


Figure II-1. Atmospheric Noise

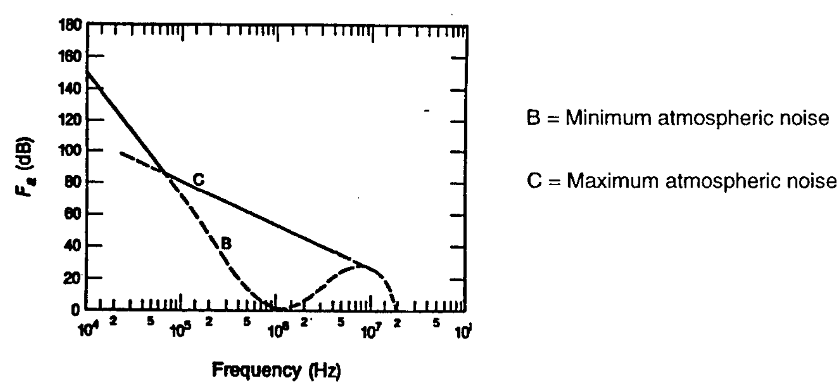


Figure II–2. Atmospheric Noise at Higher Frequencies

C. SUSCEPTIBILITY TO GROUND CLUTTER

In the real world of detecting mines and UXO, many forms of clutter may exist at the surface. The presence of cultural clutter from the surface to a depth of 30 cm can be the largest source of unwanted signals. Cultural clutter can cause large numbers of false alarms and fundamentally change the detector field performance from that exhibited in a laboratory setting. The relatively high proximity of the surface clutter to the detector, vis-à-vis the target, results not only in larger target returns, but also more complex returns in both the time and frequency domains. For detector designs to effectively find small targets such as antipersonnel mines, it is important that the antenna size and sensitivity pattern be optimized to clearly distinguish between two small targets. In fact, this issue gets to the core of the present detection capability. What tradeoffs in antenna size and sensitivity result in optimized performance in the time domain and frequency domain against small targets such as antipersonnel mines? The problem of surface clutter can be dealt with operationally for UXO detection by clearing or cleaning up surface objects as they are detected and making return trips to find buried UXO. This procedure is not compatible with mine clearance operations and places more difficult requirements on detector performance.

D. SENSITIVITY TO HEIGHT ABOVE SURFACE

The response of EMI detectors varies with the total distance from the target: the strength of the return signal falls off as d^{-6}, where d is the distance from the detector to the target. The closer the detector head is placed to Earth's surface, the larger the signal induced in the search coil. Operationally, the sensitivity to height becomes an issue in areas heavily overgrown with vegetation or with soils containing magnetite. Since the detector head is usually swept over the ground surface to interrogate suspect target areas, the detector sensitivity at one end of the swing can be substantively different than at other points along the swing. To compensate, time-domain EMI induction can be used to determine target distance. The height sensitivity is also important if metal detection data is to be fused with data from other sensors. Finally, the height of the detector head presents special challenges for the use of signal processing because of the variation of the signal as the detector head is swung at varying heights above the ground.

E. SENSITIVITY TO TILT ANGLE

Different antenna and search coil configurations produce different field patterns beneath Earth's surface. Some configurations are more sensitive to tilt angle so that even small deviations from the horizontal seriously change the detector's ability to find targets. For antennas that use bucking fields to produce nulls along a centerline, detector tilt changes also affect the area being interrogated. This is important operationally because the operator may not sweep the correct area or may be scanning at a substantially reduced sensitivity. The effect is magnified when the detector head is being swung, particularly at the two ends of the swing. The areas being interrogated are not directly beneath the detector head, and the smaller amplitude returns from the areas actually being interrogated may not be sufficient for target detection.

F. SENSOR VELOCITY

The speed at which an EMI detector can operate is limited by its antenna configuration, its radiation pattern, and its electronic circuit design. Clearly, there are major advantages to be gained in detection and false-target discrimination if the detector can remain stationary over the target and collect multiple data sets. Operationally, however, the detector must be moved to identify each potential target. There are two extremes in the land platform approaches towards minimizing the time to detect mines. At one extreme is a threshold technique that permits vehicle speeds of 10–20 mph and effectively uses the size of the antitank (AT) mine signal to discriminate mines and UXO from background and clutter. This approach ignores the smaller antipersonnel land mines. At the other extreme, humanitarian demining detection with handheld detectors may use interrogation times of several minutes per square foot to find the smaller targets such as antipersonnel mines.

G. SENSITIVITY TO SPATIAL POSITIONING OF THE DETECTOR

Every detector has a "sweet spot" through which the detector must pass to successfully find buried targets. This spot can be found by moving the detector at successively longer distances from the center point of the target. Because the size of the target and its burial depth affect the measured sweet spot, the sweet spot needs to be stipulated for the most demanding mine and UXO targets. Defining the size of the "sweet spot" then gives the rate at which the detector can survey an area to find mines and UXO.

H. RECOMMENDATIONS

JUXOCO established a baseline for threshold metal detectors in AN PSS-12 experiments conducted at Fort A.P. Hill. NRL is in the process of establishing baseline performance of EMI detectors fused with magnetometers for the detection of UXO. If these data are accepted as baseline performance, there remains the question of addressing the areas needing new experiments and analyses using time-domain and frequency-domain techniques. Ideally three new research instruments could be created for the express purpose of finding and identifying small targets in clutter: (1) detector optimized for high-sensitivity frequency measurements; (2) detector optimized for fast time-constant measurement; (3) combined time- and frequency-domain detector to compare the performance of (1) and (2). This strategy is notionally depicted in Figure II-3.

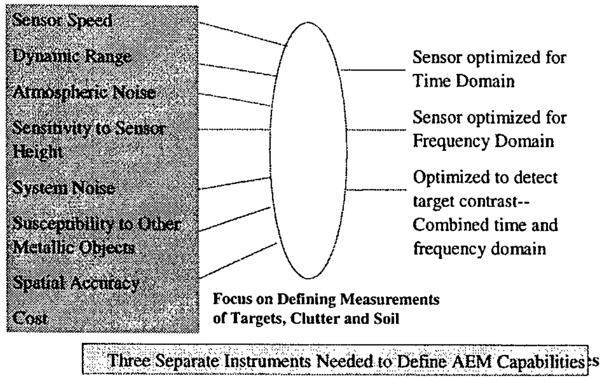


Figure II-3. Sensor-Based Issues: Tradeoffs in Sensor Development

It is recommended that the JUXOCO establish the following baselines and work toward the development and use of the following metal-detection instruments:

- Use the JUXOCO AN PSS–12 and Geophex GEM–3 tests as a baseline for EMI threshold and EMI frequency-domain testing
- Use the NRL JPG EMI/magnetometer data as a baseline for fusion of EMI and magnetometer sensors
- Model, construct, and test a frequency-domain detector optimized to find small targets and voids
- Model, construct, and test a time-domain detector optimized to find small targets and voids
- Model a combined time/frequency domain detector. If modeling results offer potential improvements, construct and test a combined time/frequency domain detector optimized to find small targets.

III. TARGET-BASED ISSUES

Target-based issues include both the soil and the target properties that affect the electromagnetic response to induced signals, including target size, burial depth, shape, and orientation, as well as clutter and soil properties.

A. TARGET SIZE

Previous analytic studies have demonstrated that EMI signals generated by buried targets are proportional to the target volume. Longer time constants are generally defined in terms of the target size, its conductivity, and its permeability. Small targets generally have smaller induced flux and evidence smaller signals for detection. For simple threshold measurements this translates into a need for greater sensitivity. For frequency-domain measurements smaller target size performs best with the sweet spot approximately the same size as the target. Smaller targets mean shorter time constants. As targets get smaller it becomes more difficult to measure the amplitude of the return signal and to measure the corresponding decay time constant.

B. BURIAL DEPTH

As discussed in section I.A, active EMI detection capability falls off as D^{-6}, where D is the distance from the detector to the target. Clearly, greater burial depth translates into smaller SNR and a greater degree of difficulty in target detection and identification. The difficulty is further compounded when the detector is required to perform against small targets such as antipersonnel land mines in a wide variety of soil types.

C. TARGET SHAPE

Because EMI target return signals are proportional to the target volume, the shapes of the targets can be used as the basis for target classification. Target classification can be viewed as a form of inverse scattering in which the measured data is matched to one or more target shapes. Maxwell's equations describe the electromagnetic field produced by the target. Since the fields are determined by the relative positions of the parts of the scattering target surface, the characteristics of the electromagnetic field will be different for different target geometries. The measured fields thereby identify the target that caused the scattered field. The difficulty of identifying target shape increases as smaller targets are measured in a wide variety of soil types and soil moisture ranges.

D. TARGET ORIENTATION

EMI detectors will produce different responses to similar targets in different orientations. For example eddy currents produced by the sensor's exciting field in a metal firing pin depend on the orientation of the pin with respect to the polarization of the field. Experiments with EMI threshold detectors have shown the inability of the detector to find some low-metal mines in specific mine orientations. Because the orientation effects are most pronounced for small nonmetallic objects, it is important to measure the responses with the research instruments at different vertical and horizontal target orientations.

E. CLUTTER

In general, detectors are developed and tested in a sandbox in which the response of the buried target can be measured and reproduced. Previous experience has always shown a large difference in detector performance in the field from that measured in the laboratory. Unwanted signals from ground clutter can be the largest contributor to the noise factor. Ground clutter includes both surface and buried debris, as well as the natural effects of an inhomogeneous soil in which the target resides. In field experiments, clutter gives rise to large numbers of false alarms. Changes in weather cause changes in the response of detectors to clutter, even at fixed test sites. Therefore, field experiments experience day-to-day variations in observed clutter, even in the absence of a target set.

Resolution of clutter from mines or UXO requires spatial or temporal resolution of the EMI signal. This is precisely what is potentially offered by the frequency and time domain measurements over that obtainable from traditional threshold techniques. Specific features of the targets and the clutter objects themselves can be used for identification. Ideally, targets and clutter could be separated through their material properties such as permeability, conductivity, and permittivity. Although nothing this simple has been demonstrated with field data, success in target identification and discrimination of clutter has been obtained for data acquired in both the frequency and the time domain. These successes were derived by focusing on identifying feature spaces in which different targets could be identified.

F. SOIL PROPERTIES

Different soils have different electromagnetic properties. The amount of moisture and the amount of magnetite present also changes the electromagnetic properties of soils. The variation of the permeability and conductivity of soils has a much larger impact on detection of small targets than of large targets. Experiments with large targets buried in moist soils have exhibited relatively minor changes in the frequency-domain signatures and time-constant decays. Major changes occur in both the frequency and time domain for smaller targets in conductive media. Detectors experience difficulty with increased density of magnetite. Typically, many detector designs are unable to null out the background while retaining sufficient sensitivity to detect mines in magnetite soils.

G. RECOMMENDATIONS

Figure III-1 presents the target-based issues for six EMI detection variables for different technology approaches for improved detection.

Technology	**Target Size**	**Target Shape**	**Burial Depth**	**Clutter**	**Soil Properties**	**Orientation**
Time Domain	Time constants decrease with smaller size targets and voids.	Changes in time constant more easily detected with larger size targets.	Smaller signal to noise (S/N) with increased burial depth.	Superposition of signals from nearby clutter on target signature. Small clutter objects difficult to identify.	Higher conductivity soils have longer time constants which may mask small target signatures.	Relatively insensitive to target orientation.
Frequency Domain	Significant decrease in S/Nfor smaller targets and voids.	Significant changes for different shapes with same volume.	Smaller S/N with increased burial depth.	Response to nearby clutter depends on sensitivity pattern of detector. Difficulty with small targets.	Higher conductivity soils will dominate frequency spectrum for small targets. Voids more easily detected at higherconductivities.	Symmetric response directly over target enhances discrimination. Sensitive to orientation of sensor to target.
Combined Time and Frequency Domain	Detection andidentifi-Cation time increases with decreased target or void size.	Identification of larger targets. Potential improvement in detection of small targets and voids.	S/N decreases as ↑for both time and frequency domain measurements.	Difficulty in identifying small clutter objects.	Contrast recognition and enhancement needed for small targets in conductive soils.	Strengths of time and frequency domain are complementary.
Needs	*Theory and experiments of small targets.*			*Target resolution in presence of clutter. Meassure different clutter objects.*	*Measure small targets in different soils.*	*Identify primary sensor modes*

Figure III-1. Target-Based Issues for Six EMI Detection Variables

None of the three EMI techniques have yet demonstrated the discrimination capability exhibited with large targets. Both theoretical analysis and experiments are needed in which all three EMI techniques are optimized to find small targets. Using the detectors specified in II.H, small targets and target voids should be specified at the size of the U.S. M–14 mine. Both experiments in air and in soil should be conducted to define the capabilities of these technology options.

There are two clutter issues. The first is the ability of each technological approach to identify a target in the presence of clutter. Each detector approach measures a composite signal of both the target and the clutter. Therefore, it is important that some salient features of both the target and the clutter be reliably extracted from the composite data. The second clutter issue is the ability of a sensor to distinguish a clutter object from a true object in the absence of other targets or clutter. Therefore, it is necessary to measure and calculate both the target and the clutter characteristics.

The Defense Advanced Research Projects Agency (DARPA) conducted clutter data in which magnetometers, EMI sensors, radar, and infrared sensors were to survey four different sites. Post-data-collection algorithm work resulted in a significant decrease in the density of false alarms. New clutter experiments need to be conducted using the EMI frequency, time, and joint frequency/time domain instruments discussed in II.H. The experiments need to be repeated for different weather conditions and at different times of the year. Specific man-made clutter items should be placed into the test for characterization in a number of different positions and burial depths.

There is a need to both model and measure small targets and voids in different soils to determine their frequency spectra and time constants. Because UXO can be buried more deeply than mines, it is recommended that UXO frequency and time responses be calculated and measured to depths of 1 m.

There is a need to identify the primary and secondary modalities for a combined sensor. Enough data needs to be collected to demonstrate the performance of the joint frequency/time domain sensor relative to detector performance optimized independently in the time and frequency domains. Finally, there is a need to determine the range of sensor responses in the frequency domain where the detection head never passes over the center of the mine. This last issue is important principally because much of the recent data in the frequency domain is based on taking data either directly over the target or at symmetric positions about the target. In the field, it is rare that all that information will be available to identify targets or to establish a target detection.

IV. MODELING AND MEASUREMENTS

Traditionally, EMI detectors reflect tradeoffs in technical, operational, and cost factors. One of the major operational issues is the speed at which the detector can be used. Although vehicle-mounted detectors clearly place a high value on speed, handheld detectors typically are used at speeds of 0.2 m^2/sec (or greater) in their search modes. Handheld detectors are generally designed to produce an alert in a fast sweep mode so that the operator will slow down or stop and try to locate the source of the alarm. In most handheld detectors there is no secondary detection mode. Some of the more expensive detectors have a variant or alternate detection mode, but again, these modes are generally used with the detector head in motion. Alternatively, some operators find the mine location, and then rotate the combined transmit and sensor head to distinguish between different targets or to determine target location. The important point is that this generic threshold approach does not work well in discriminating mines from clutter once a potential target has been located. An improved technique would employ secondary or tertiary EMI detectors to interrogate the metal target in both the time and the frequency domains. As the target size decreases, the greater the likelihood of encountering clutter of the same dimensions. The increase in clutter leads to two problems in target identification. First, the superposition of clutter signals can alter the "signature" of the true target. Second, the larger the range of clutter type objects, the more difficult it is to identify true targets from clutter objects. To meaningfully address these difficulties, it is important that secondary sensors provide reliable, accurate information on potential targets.

A. DETECTOR DESIGN

Historically, a number of different existing detectors are used to test a spectrum of targets. With the progress that has recently been demonstrated with frequency- and time-domain detectors against large targets, it is clear that if we want to identify small targets we will need to design separate time-domain, frequency-domain, and combined time/ frequency-domain detectors that are optimized for small targets. The variables used in the design and construction of each of these instruments could be used to validate the measured performance. This approach would show the limits of performance for each sensor approach and, more important, would delineate the functional dependence of the design variables. The suggested design goals would include detecting and identifying targets such as a small (<5 cm diameter) submunition or the U.S. M–14 mine at depths of 50 mm in loamy soil.

B. SYMMETRY

Recent experimental data, together with signal-processing results, have demonstrated the importance of operating time- and frequency-domain detectors directly centered over the target. Although it may be intuitively clear that symmetric operations about an object imbued with manmade symmetry leads to improved signal-processing results, it is not clear how big the sweet spot will be for small targets of different shapes buried at different depths in different types of soils. Because target symmetry can play such a vital role in separating mines and UXO from clutter, the first road to understanding can only come through modeling. Similarly, it is vital to know how the time- and frequency-domain signatures are changed for off-center detection.

Because smaller items of cultural clutter can be the same size or general shape of true targets (UXO and mines), modeling permits comparison of targets and a variety of natural and cultural clutter. Cultural clutter can also have inherent target symmetry. Modeling can provide a priori comparisons of mine and UXO targets to a wide variety of clutter objects. Finally, the signature of nearby clutter can be superimposed on the signature of true targets. Modeling allows different design approaches to be tested and thereby define potential uses of symmetry detection approaches.

C. DISCRIMINATION OF NEARBY TARGETS

When two targets are placed beside one another, the observed signal is a superposition of the flux returns from both targets. This is a common occurrence in field tests. Small clutter items may be near mine or UXO sites. On the battlefield, booby traps use several mines buried close together or on top of one another. Theoretical calculations are necessary to simulate different detector designs to optimize the time or frequency response to resolve nearby objects. The calculations in turn can be used to validate the results from measurements against selected small targets.

D. DIFFERENT SOIL TYPES

Measurements with present detectors have shown the difference between airborne and burial tests for small targets. Soil conditions that exhibit high conductivity, high permeability, or both traditionally cause the most difficulty for present detectors. As detector designs are optimized for small targets, the modeling process should include calculations that consider a range of loam and magnetite soils with different moistures. The effect of different soils on void detection should also be addressed during the design stage and the results validated during experimental testing of the new detector designs.

E. CLUTTER

A small set of clutter objects typical of field conditions for mine and UXO detection should be modeled against different detector designs. The clutter set could contain small shell casings, nails, belt buckles, etc., that represent conductive material found in proximity to mine and UXO targets. The results of these calculations should then be compared to measurements using the newly designed detectors.

F. MEASUREMENTS

It is recommended that a series of laboratory tests be conducted both in air and in different soils. The purpose of the laboratory measurements is to validate the theoretical performance of the three new detectors (time-domain, frequency-domain, and combined time- and frequency-domain detectors). In practice, it may be more practical at the beginning to design and test the time-domain detector and the frequency-domain detector. Having optimized and tested these two different types of detectors, the tradeoffs can be more clearly delineated in the design of the combined time- and frequency-domain detector. It is important that the experimental tests replicate as accurately as possible the variable types and variable ranges used in the modeling design phase. Differences between modeling predictions and experimental measurements need to be resolved so that it will be possible for later scientists and engineers to meaningfully design new equipment. Ultimately, some field measurements should be performed with these new detectors against targets in the pilot test site at Fort A.P. Hill for comparison with the earlier PSS–12 and GEM–3 results.

G. RECOMMENDATIONS

It is recommended that theoretical calculations be performed to optimize the performance of separate time-domain and frequency-domain detectors against small UXO and clutter targets (UXO, mines, and voids) the size of M–14 mines. Having theoretically demonstrated the feasibility of these approaches, prototypes need to be constructed and tested in a series of laboratory experiments in which the targets are measured in "air" and buried in a variety of soils to depths of 50 mm. Differences in model predictions from experimental measurements need to be documented so that future detectors will be based on proven design approaches. The role of symmetry measurements needs to be documented through theoretical calculations. Specifically, target signatures need to be calculated and measured for instances in which the detector head does not pass directly over the center of the target. Modeling should be used to define the potential uses of symmetry detection approaches as well as to define the physical limitations and boundary conditions associated with using a symmetry-based recognition technique. Modeling of nearby targets or clutter is also necessary to define the criteria to be used in optimizing the detector sweet spot and detector sensitivity.

V. SIGNAL PROCESSING AND SENSOR FUSION

A. SIGNAL-PROCESSING TECHNIQUES

There are many forms of signal processing. They range from relatively simple signal averaging or threshold recognition techniques to more complex techniques such as signature recognition, matched filters, and regression fitting. Several methods have been applied to both time- and frequency-domain data to identify specific targets and to separate targets from clutter: neural nets, polarizability models, and Bayesian statistical methods. Bayesian approaches incorporate the statistical properties of both targets and clutter. Substantial reductions in false alarms are achieved in the ROCs for both time-domain and frequency-domain detectors using the modified GLRT. These results were shown in Figures I–4 and I–5. Figure I–6 shows the improvements in the ROC curve that can be achieved with a spatial symmetry algorithm, and Figure I–7 demonstrates the improvements using a decay curve signature algorithm. Similarly, other work has shown improvements in the ROC curves using Dempster-Shafer rules, and fuzzy logic.

These results were generally achieved with targets using 18 g or more of metallic content. Typically, the analyses were conducted for controlled data sets and with fixed experimental position of the sensor relative to the target and clutter. In most cases, the data used to conduct the analyses consisted of data points taken directly over the target or clutter. For the most part, the data evaluated do not contain variations that would be encountered by detector systems used in an operational remedial environment. These variations include the following:

- Data streams without data directly centered over the detector
- Varied detector heights
- Varied detector head tilts
- Varied target orientations
- Varied soils
- High clutter environments.

Therefore, even for the larger metallic content targets it is clear that more evaluation is needed. Just as the JUXOCO led development of well characterized data sets from its pilot test site, it is now important to expand the use of the site to investigate the variables listed above. Understanding of all of these variables is necessary before the next step can be taken to provide real-time use of the signal processing in the field.

The ability to detect and to identify small, nonmetallic targets and voids ultimately will be determined by signal to noise for new time-domain or frequency-domain sensors. The power of the modified GLRT resides in the correlations that can be achieved with multiple observations. To fully exploit the potential of time-domain and frequency-domain sensors, it is necessary to plan signal-processing tests to define the limits of target detectability for different false-alarm rates. Having theoretically optimized new EMI sensors and compared their theoretical and experimental capabilities, it is recommended that Bayesian signal-processing techniques be used to complete the process of optimizing ROC curves for EMI detectors.

B. SENSOR FUSION

Because there is such a diversity of mines, UXO, and clutter, robust detection of UXO and mines will most likely demand other types of sensors as well as signal processing. Other technology initiatives in magnetometers, ground-penetrating radars (GPR), forward-looking infrared (FLIR), and NQR are being actively investigated and are reporting significant advances in clutter rejection.

To achieve sensor fusion it is important to provide coincident sensor views of the same area. Because the data taken during this next program could be used for future fusion studies, it will be important to accurately and reliably record target orientation and sensor aspects.

The obvious approach to achieve fusion is to provide target correlations and clutter decorrelations. As the data from the EMI detectors optimized to find small targets becomes available, it should quickly be analyzed for possible fusion with GPR, NQR, IR, and other sensors. Field tests of these new detectors at the pilot test site at Fort A.P. Hill will provide the opportunity to assess the ability to fuse this data with that previously collected with the baseline measurements of the AN PSS–12 and Geophex GEM–3 detector.

C. RECOMMENDATIONS

Major improvements to the ROCs for several detectors have been recently demonstrated (see Chapter I) using a variety of advanced signal-processing techniques.

These data were generally limited to data streams in which the detector head was centered above the target, at known symmetry positions with respect to the target, or both. It is important that advanced signal-processing techniques be applied to time domain and frequency domain detectors optimized to detect small targets (i.e., less than 5 cm diameter and 5 g of metal). When advanced signal processing of these new optimized detectors is completed, there will exist a clear indication of the best performance that can be achieved with present technology and new EMI techniques. Detectors with sweet spots optimized for small targets will be significantly less sensitive to targets in near passes as opposed to direct overpasses. Therefore, it is also recommended that advanced signal-processing techniques be applied to signals obtained in the time and frequency domains in which the detector head did not pass over the center of the target/void/clutter item.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

There are a large number of active programs investigating the use of metal detectors for use in mine and UXO detection. These programs include efforts sponsored by the ARO; the Army Environmental Center, SERDP; the Waterways Experimental Station (WES); DARPA; U.S. Naval Explosives Ordnance Disposal; U.S. Army Project Manager for Mines, Countermines, and Demolitions (PM–MCD); and the Night Vision and Electronic Sensors Directorate (NVESD). Drawing from both the sponsoring agencies and the performing contracts, the JUXOCO has conducted one workshop in magnetometry and two workshops in active electromagnetics. The consensus priorities of these workshops has placed the focus on the following items:

- Measure target and clutter data in known environments
- Work towards full spectrum EMI
- Develop tests sites, protocols, and targets
- Provide EMI modeling
- Fuse magnetometry and EMI
- Work towards sensor fusion with other sensors.

In response to these priorities, the JUXOCO established a pilot test site at Fort A.P. Hill, Virginia, with protocols and targets. JUXOCO, working with the MURI program, performed baseline measurements on the AN PSS–12 mine detector and the Geophex GEM–3 detector. Leveraging the MURI investment, the JUXOCO also sponsored EMI modeling in the frequency and time domains.

Significant progress has been made in many different programs in exploiting the time- and frequency-domain EMI approach to mine and UXO detection. In addition to the progress that has been made, there are also ongoing programs directed at achieving the goals delineated in the magnetometry and active EMI workshops. SERDP has funded programs for developing full-spectrum characterization of UXO, fusion of magnetometry with EMI, and multisensor target fusion for UXO detection and identification. NVESD is developing a large time-domain EMI device to be tested as a vehicle-mounted detector.

The MURI program is being continued as a second phase to their earlier efforts. It is clear that significant progress is being made in many different programs to achieve the workshop priorities.

Given all the past and present efforts, there remains the difficulty in finding small targets that are roughly the same size as clutter objects. The issue is whether time-domain, frequency-domain, or some combination of time/frequency-domain detectors can be developed that will effectively detect targets, reject clutter, and provide target identification.

B. RECOMMENDATIONS

It is recommended that JUXOCO provide leadership to accomplish the following:

- Model, construct, and test a frequency-domain detector optimized to find small targets and voids roughly the size of the U.S. M-14 landmine.
- Model, construct, and test a time-domain detector optimized to find small targets and voids as above.
- Model a combined time/frequency-domain detector. If modeling results offer potential improvements over separate time-domain and frequency-domain detectors, construct and test a combined time/frequency-domain detector optimized to find small targets.
- Model and measure the effects of placing targets and clutter in the sensor "sweet spot" or very near the point of greatest receiver sensitivity. Clutter in close proximity to targets will alter target signatures; this effect needs to be assessed.
- Model and measure the optimized detectors in loam, sand, and magnetite soils with a range of representative soil moistures.
- Develop a set of small clutter objects to be modeled and measured.
- Preserve theoretical model calculations and data measurements so that future designs can use the model to predict and evaluate sensor performance.
- Conduct field tests at the pilot test site and compare performance of optimized detectors to baseline performance of the AN PSS–12 and Geophex GEM–3 detectors.
- Apply advanced signal-processing techniques to demonstrate the full ability of optimized EMI performance against small UXO and mine targets.

GLOSSARY

ARO	Army Research Office
AT	antitank
ATD	advanced technology demonstration
ATR	automatic target recognition
CECOM	U.S. Army Communications and Electronics Command
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOE	Department of Energy
EMI	electromagnetic induction
FLIR	forward-looking infrared
GLRT	generalized likelihood ratio test
GPR	ground-penetrating radar
JHU–APL	Johns Hopkins University-Applied Physics Laboratory
JPG	Jefferson Proving Ground
JUXOCO	Joint Unexploded Ordnance Coordination Office
MoM	method of moments
MTADS	Multi-sensor Towed Array Detection System
MURI	Multi-University Research Initiatives
NQR	nuclear quadrupole resonance
NRL	Naval Research Laboratory
NVESD	Night Vision and Electronics Directorate
OSD	Office of the Secretary of Defense
PM–MCD	Project Manager for Mines, Countermines, and Demolition
ROC	receiver operating characteristics
SEM	singularity expansion method
SERDP	Strategic Environmental Research and Development Program
SNR	signal-to-noise ratio
TEMID	time domain EMI detector (JHU–APL)
TNT	trinitrotoluene
UXO	unexploded ordnance
WES	Waterways Experimental Station

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This report assesses the current state of research in the use of metal detectors to detect and identify unexploded ordnance and landmines. This report recommends that new time-domain, frequency-domain, and combined time/frequency-domain detectors be theoretically designed, constructed, and tested against small targets and clutter roughly the size of the U.S. M-14 mine (<5 cm diameter, <5 g metal). The report further recommends that the design and test information be made publicly available to enable future design and analyses improvements. It is also recommended that advanced signal-processing techniques be used to complete the definition of optimized electromagnetic induction performance against small targets.

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